Published in *J. Low Temp. Phys.* **119**, 249-256 (2000).

Does the Kibble Mechanism Operate in Liquid ^{4}He?

P.C. Hendry, N.S. Lawson, P.V.E. McClintock

Department of Physics, Lancaster University, LA1 4YB, UK

A rapid passage of liquid ^{4}He through the lambda (superfluid) transition is expected (W.H. Zurek, Nature **317***, 505; 1985) to result in the production of topological defects (quantized vortices) through the Kibble mechanism, the same process that is believed to have produced cosmic strings at the GUT phase transition of the early universe. But recent experiments (Dodd et al, Phys. Rev. Lett* **81***, 3703; 1998)) show that the density of vortices created, if any, seems to be smaller than predicted by a factor of at least 100. Possible ways of improving the sensitivity of the experiment are discussed.*
PACS numbers: 11.27.+d, 05.70.Fh, 11.10.Wx, 67.40.Vs

1. INTRODUCTION

The Kibble mechanism[1] is expected to operate when a system passes sufficiently fast through a continuous phase transition. It results in the formation of topological defects because of an event horizon whereby small regions of new phase are initially formed out of causal connection with each other. It was introduced in connection with the grand unified theory (GUT) symmetry-breaking phase-transition in which cosmic strings[2] are believed[3] to have been created in the early Universe. Later, Zurek pointed out[4–6] that closely analogous behaviour is to be anticipated when liquid ^{4}He passes through its lambda (superfluid) transition, resulting in the creation of quantized vortex lines, the superfluid analogue of cosmic strings. He estimated the vortex density to be anticipated, in terms of the timescale of the passage through the transition.

The lambda transition cannot, in practice, be traversed quickly by isobaric temperature reduction, because of the well known specific heat singularity at T_λ. Zurek pointed out,[4–6] however, that an adiabatic *expansion* of He I through the transition could in principle be effected rapidly. The first such experiment[7] seemed to show vortex creation at approximately the predicted density. Later, however, a refined version of the experiment[8,9] led to the conclusion that the initial results had been misleading because of inadvertent vortex creation caused by nonidealities of the expansion process (resulting in bulk flow): it was concluded that there was no measurable vortex creation at all. Any vortices being produced were apparently at a density at least 100 times smaller than expected.

These results are not matched by those obtained from other systems. In particular, phase transitions in liquid crystals[10–12] and in liquid ^{3}He[13,14] have been shown to result in extensive defect formation at densities consistgent with the theoretical predictions. The reason why the Kibble mechanism should work in liquid crystals and liquid ^{3}He, but apparently not in liquid ^{4}He, is not known. One possible explanation[15] involves the effect of thermal fluctuations very close to the transition, tending to unwind the order parameter; it is also possible that the vortices decay too fast to be observed.[16,17] The situation remains unclear and further experimental input is highly desirable.

We discuss below some ways in which the ^{4}He experiment might be further enhanced so as to make it more sensitive to any vortex creation that does occur. Section 2 outlines the operation of the present expansion system. Section 3 discusses ways in which a faster passage through the lambda transition might be achieved, and other possible enhancements; Section 4 summarises the discussion and draws conclusions.

2. THE PRESENT ^{4}He EXPERIMENT

The experiment has already been described in detail,[9] but we outline briefly the salient features relevant to the present discussion.

The underlying idea[4] is quite simple. A small isolated volume of He-I is initially held at pressure P_i, and temperature T_i, just above the temperature $T_\lambda(P_\mathrm{i})$ of the λ-transition. The arrangement is shown schematically in Fig. 1. The liquid is held in a disk-shaped cell whose cylindrical outer wall is formed from a bronze bellows; its pressure is maintained by compression between two heavy metal plates. The lower, moveable, plate is held in position by a pull-rod from room-temperature with a latching trigger mechanism on the cryostat top-plate.

In an experimental expansion, the trigger is squeezed, releasing the pull-rod, and allowing the lower plate to descend under the large force provided by the compressed liquid. A stop (in reality, adjustable) on the top-plate limits

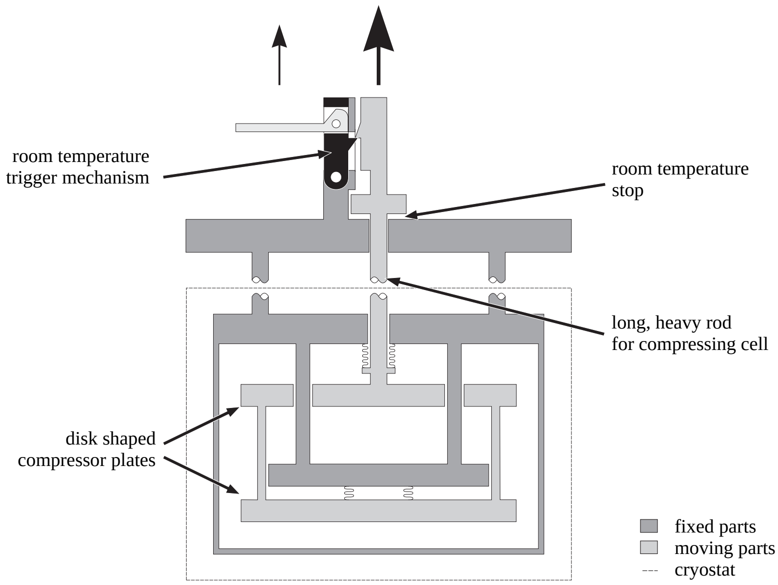

Fig. 1. Schematic diagram showing the mechanism of the original [7,8] expansion geometry. Note that the trigger mechanism and stop are at room temperature on the cryostat top-plate, necessitating the use of a long pull-rod for compressing the cell between the lower moving plate and the adjacent fixed plate. The disk-shaped compressor plates (see Fig. 3(b)) were also relatively heavy.

the movement and thus determines the final pressure P_{f} and temperature T_{f}. Immediately following the expansion, a sequence of second sound pulses is propagated across the cell: vortices are detected by the attenuation that they produce.

The measured evolution of the second sound amplitude[8,9] is shown in Fig. 2. Rather than growing in the manner anticipated, as the expected vortex tangle decayed, there is no obvious change in the height of the signal at all, i.e. no measurable vortex creation at all. The curves show the calculated behaviour for different initial vortex line densities; under the conditions of the experiment, it was expected that the initial vortex density would be $\sim 4 \times 10^{12}$ m^{-2}, which plainly it was not.

We make two additional comments on these results. First, the signals used to construct Fig. 2 tend to be very noisy at early time, as indicated by the error bars. This effect seems to arise from mechanical vibrations caused by the expansion process. Secondly, the densities of vortices that

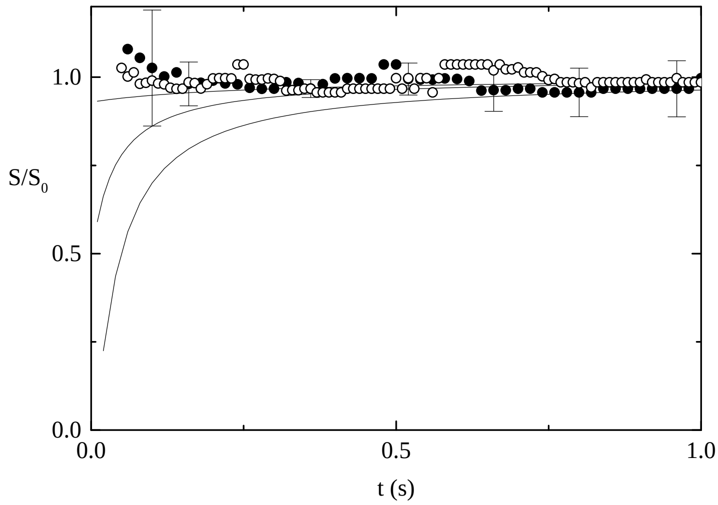

Fig. 2. Evolution of the second sound amplitude S with time following two expansions of the original cell [8] at $t = 0$ (data points) under identical conditions; S_0 is the signal amplitude in the absence of vortices. The curves refer to calculated signal evolutions for different initial vortex line densities, from the bottom, of $10^{12}, 10^{11}, 10^{10}$ m^{-2}. The density expected on the basis of (1) was $\sim 4 \times 10^{12}$ m^{-2}. Note the large scatter at early time.

were expected on the basis of the original predictions[4,5] were so large that no special attempt was made to optimise the experiment. But, given the unexpectedly null result, efforts in this direction are clearly needed and may be expected to pay dividends.

3. AN ENHANCED ^{4}He EXPERIMENT

One way to provide a more sensitive test of the ideas underlying the Kibble/Zurek mechanism is to repeat the experiment under conditions where the predicted initial vortex density L_i is larger. Zurek's[6] estimate was that

$$L_i = \frac{1.2 \times 10^{12}}{(\tau_Q/100\,\mathrm{ms})^{2/3}} \qquad [\mathrm{m}^{-2}] \qquad (1)$$

where the quench time τ_Q, characterising how long it takes to traverse the transition, is given by

$$\tau_Q = \frac{1}{\left(\frac{d\epsilon}{dt}\right)_{\epsilon=0}} \tag{2}$$

and

$$\epsilon = \frac{T_\lambda - T}{T_\lambda} \tag{3}$$

is a parameter specifying the distance from the transition temperature T_λ; note that Zurek's more recent estimates of L_i[18] are somewhat smaller than implied by (1). Thus, the only way to increase L_i is to reduce τ_Q by increasing the rate of expansion $\left(\frac{d\epsilon}{dt}\right)_{\epsilon=0}$. In principle one could consider a forced expansion, rather than allowing the cell to expand under its own internal pressure as at present. Given the magnitudes of the forces involved (equivalent to 147 Kg weight for the present cell with $P_i = 30$ bar), and the difficulties already being experienced with vibration after the expansion is abruptly halted, this option appears difficult. A better option must be to try to lighten all the moving parts so as to increase the acceleration for any given pressure.

In the original apparatus (Fig. 1) most of the moving mass lay in the two disk-shaped compressor plates, the long pull-rod extending up to the cryostat top-plate at room temperature, and in the trigger mechanism. In a new cryostat, now being designed, we plan several radical changes to the expansion mechanism, as sketched in Fig. 3. The disk-shaped plates will be replaced by the "spider-shaped" ones shown in Fig. 3(a). The trigger mechanism will be lightened as much as possible consistent with having the necessary strength, and placed on the top of the vacuum can flange in the main liquid ^{4}He bath (Fig. 3(b). The stop will be placed immediately adjacent to it, thus eliminating most of the length of the long pull-rod from room temperature. A means of applying the large force (big vertical arrow) needed to compress the liquid will still be needed, of course, but could be provided by a chain or wire, or by a rod not bonded rigidly to the moving parts: it is needed only initially, to compress the liquid until the trigger latches and can then be loosened. We calculate that, even without resort to special materials, these changes should reduce the mass of the moving components by $\sim$80 %. From (1) this would imply an increase in L_i by a factor of $\sim$3.

It is clear from the results of Fig. 1 that it would be particularly advantageous if the noise on the signals at early time could be reduced. It is believed to result in large part from longitudinal vibrations in the pull rod, which is in tension. These vibrations result in small changes in the length – and therefore the pressure and temperature – of the sample, contributing a

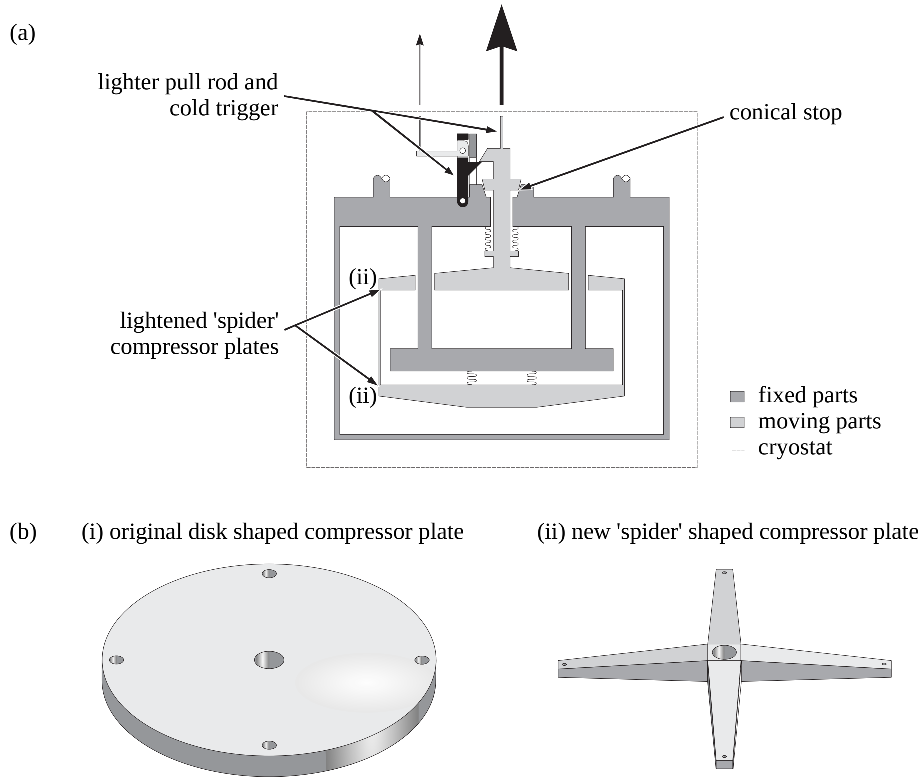

Fig. 3. Schematic diagram showing proposed modifications of the expansion mechanism (c.f. Fig. 1). (a) General view: trigger and stop are now in the main ^{4}He bath; a rigidly attached pull-rod is no longer needed; and the stop is conical. (b) The two compressor plates are now "spider"-shaped. The cell is compressed between the fixed plate and the lower "spider".

large noisy component to the second sound signals. Elimination of most of the length of the pull rod (c.f. Figs. 1 and 3) should also, therefore, substantially reduce the effect probably also shifting it to higher frequencies where it will be easier to filter out.

A second way of reducing the shock at the end of the expansion, and thus the ensuing vibrations, is to replace the flat stop with a conical one (Fig. 3). Most of the energy generated during the expansion will thus be dissipated by friction and dumped in the main liquid ^{4}He bath. The optimal cone angle is yet to be determined, but it must obviously be made small enough to be dissimilar to the flat stop of Fig. 1, but larger than that at which a cold weld might occur.

It is impossible to be quantitative about the extent to which noise at early time might be reduced by these changes, but a guess of a factor of 3–4 seems not unreasonable.

4. CONCLUSION

It is concluded that, with some redesign, it should be not be too difficult to enhance considerably the sensitivity with which (1) can be tested, potentially enabling the lower bound on the disagreeement between experiment and theory to be increased by an order of magnitude to $\sim 10^3$. Of course, if some vortex creation can be detected, it will then be necessary to test carefully whether it arises via the Kibble mechanism or stems from conventional flow processes[7–9] caused by nonidealities during the expansion.

ACKNOWLEDGMENTS

We acknowledge valuable discussions or correspondence with S.N. Fisher, A.J. Gill, R.A.M. Lee, R.J. Rivers, W.F. Vinen, G.A. Williams and W.H. Zurek. The work was supported by the Engineering and Physical Sciences Research Council (U.K.), the European Commission and the European Science Foundation.

REFERENCES

1. T.W.B. Kibble, *J. Phys. A* **9**, 1387 (1976).
2. A. Vilenkin and E.P.S. Shellard, *Cosmic Strings and Other Topological Defects* (Cambridge University Press, Cambridge, 1994).
3. A.J. Gill, *Contemporary Phys.* **39**, 13 (1998).
4. W.H. Zurek, *Nature* **317**, 505 (1985).
5. W.H. Zurek, *Acta Physica Polonica B* **24**, 1301 (1993).
6. W.H. Zurek, *Phys. Rep.* **276**, (1996).
7. P.C. Hendry, N.S. Lawson, R.A.M. Lee, P.V.E. McClintock and C.D.H. Williams, *Nature* **368**, 315 (1994).
8. M.E. Dodd, P.C. Hendry, N.S. Lawson, P.V.E. McClintock and C.D.H. Williams, *Phys. Rev. Lett.* **81**, 3703 (1998).
9. M.E. Dodd, P.C. Hendry, N.S. Lawson, P.V.E. McClintock and C.D.H. Williams, *J. Low Temperature Phys.* **115**, 89 (1999).
10. I. Chuang, N. Turok and B. Yurke, *Phys. Rev. Lett.* **66**, 2472 (1991).
11. I. Chuang, R. Durrer, N. Turok and B. Yurke, *Science* **251**, 1336 (1991).
12. M.J. Bowick, L. Chander, E.A. Schiff and A.M.Srivastava, *Science* **263**, 943 (1994).
13. C. Bäuerle, Y.M. Bunkov, S.N. Fisher, H. Godfrin and G.R. Pickett, *Nature* **382**, 332 (1996).

14. M.H. Ruutu, V.B. Eltsov, A.J. Gill, T.W.B. Kibble, M. Krusius, Y.G. Makhlin, B. Placais, G.E. Volovik and W. Xu, *Nature* **382**, 334 (1996).
15. G. Karra and R.J. Rivers, *Phys. Rev. Lett.* **81**, 3707 (1998).
16. G.A. Williams, *J. Low Temperature Phys.* **93**, 1079 (1993).
17. G.A. Williams, *Phys. Rev. Lett.* **82**, 1201 (1999).
18. P. Laguna and W.H. Zurek, *Phys. Rev. Lett.* **78**, 2519 (1997).